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Design For Six Sigma with Critical-To-Quality Metrics for Research Investments

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Design for Six Sigma with Critical –To-Quality Metrics for Research Investments

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Abstract

Design for Six Sigma (DFSS) has evolved as a worthy predecessor to the application of Six-Sigma principles to production, process control, and quality. At Livermore National Laboratory (LLNL), we are exploring the interrelation of our current research, development, and design safety standards as they would relate to the principles of DFSS and Six-Sigma. We have had success in prioritization of research and design using a quantitative scalar metric for value, so we further explore the use of scalar metrics to represent the outcome of our use of the DFSS process. We use the design of an automotive component as an example of combining DFSS metrics into a scalar decision quantity. We then extend this concept to a high-priority, personnel safety example representing work that is toward the mature end of DFSS, and begins the transition into Six-Sigma for safety assessments in a production process. This latter example and objective involves the balance of research investment, quality control, and system operation and maintenance of high explosive handling at LLNL and related production facilities. Assuring a sufficiently low probability of failure (reaction of a high explosive given an accidental impact) is a Critical-To-Quality (CTQ) component of our weapons and stockpile stewardship operation and cost. Our use of DFSS principles, with quantification and merging of CTQ metrics, provides ways to quantify clear (preliminary) paths forward for both the automotive example and the explosive safety example. The presentation of simple, scalar metrics to quantify the path forward then provides a focal point for qualitative caveats and discussion for inclusion of other metrics besides a single, provocative scalar. In this way, carrying a scalar decision metric along with the DFSS process motivates further discussion and ideas for process improvement from the DFSS into the Six-Sigma phase of the product. We end with an example of how our DFSS-generated scalar metric could be improved given success of our future research investments in impact safety scenarios.

1 Introduction

Our goal in this work is to use examples to illustrate three key points that provide a linkage between DFSS, product development, and systems engineering. These points are that:

1. The DFSS process, when linked to a scalar metric quantity such as the Benefit / Cost Ratio (BCR), can quantify what might otherwise be a qualitative, judgment based path forward for research or operations. This quantitative DFSS+BCR defense is not meant to replace expert judgment; only to augment, focus, and reflect the expert judgment process in a quantitative way.
2. During DFSS, we must remember that the strings of numbers often come from models of a process and of physics. Often these models must make do with incomplete physics and incomplete data. It is very important to take account of this fact of model use and to quantify model confidence throughout the DFSS process. We will illustrate the difference this can make in one of our examples.

3. DFSS should not be viewed as a one-time activity. The DFSS process should be revisited whenever there is a significant change in knowledge about the physics, likelihoods, benefits, or consequences of the system or product under consideration.

Design and new product development often involves qualitative goals and depends on advances in research and development yet to come to fruition. Because of these and other factors, the design process will always contain a blend of qualitative and quantitative aspects. The Design For Six Sigma (DFSS) process is ideally suited to deal with both qualitative and quantitative aspects, and has the added advantage of a smooth transition into the production phase use of Six-Sigma principles. DFSS and Six-Sigma began with a very quantitative basis, namely a goal of nearly-zero defects per million in a product or process. Six-Sigma formally refers to a long term defect level of less than 4 Defects Per Million (DPM).

There is no special “magic” about DFSS or Six-Sigma, except the benefits of established goals, adherence to an established, rigorous process, and the combination of qualitative (judgment based) and quantitative (often reliability and risk based) design and implementation. Several variants of implementation for DFSS are outlined in (Hu et al, 2004), including:

IIDOV: Invent, Innovate, Develop, Optimize, Verify

CDOV: Concept, Design, Optimize, Verify

IDDOV: Identify, Define, Develop, Optimize, Verify

DCOV: Define, Characterize, Optimize, Verify

DMADV: Define, Measure, Analyze, Design, Verify

DMAIC: Define, Measure, Analyze, Improve, Control

The latter of the implementations, DMAIC, is typically where the DFSS design and development process transitions into Six-Sigma production, quality, and defect and cost reduction. In each of these implementations the “Identify” or “Define” phase is where the Critical-To-Quality (CTQ) issues are identified, so they can be worked throughout the rest of the DFSS or Six-Sigma process. It is in this phase where methods such as QFD or Quality Function Deployment (Kogure and Akao, 1983) are first used to help design and implement the correct process and product. Usually, there will be more than one “Customer Want” in QFD. For example, in the main example topic of this paper, we can summarize the “Customer Wants” for impact safety of explosives as:

1. Provide a quantitative basis for a sufficiently low risk assessment in handling safety.
2. Assess the proper balance of models and experiments needed.
3. Obtain these objectives while minimizing risk and direct cost

2 Does our product justify the use of DFSS and Six-Sigma?

High explosives used in research and designs at LLNL are formulated, designed, and used with safety as a top priority. There is only a miniscule likelihood of “detonation” of the explosive during handling or logistics scenarios, but we also wish to assure a sufficiently low likelihood of even an explosive reaction, such as the reaction shown in the impact test sequence in Figure 1.

Safe handling and testing of high explosives requires a careful balance of explosive handling and mitigation of the occurrence of scenarios that might lead to an explosive impact, along with modeling and experimental work to assess the likelihood of an explosive reaction if an accidental impact did occur.

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Figure 1. Explosive Reaction during “Steven Test” (Switzer et al, 2003) for impact safety.

One of our goals should be to suggest a way to capture the outcome of the QFD process (and the DFSS process as a whole) in a single metric. The metric we will choose is the Benefit / Cost Ratio (BCR), as described in (Nitta et al, 2004). Quantitative use of the BCR requires that each term be expressed in dollar equivalents as benefit \$B or cost \$C.

In a previous work (Nitta et al, 2004), we discussed the issue of explosive impact safety using a systems engineering construct, and worked our way up a pyramid of activity to the BCR, as depicted in Figure 2. Our focus for DFSS appears in the “Reliability Methods” layer of the Figure 2 pyramid. However, when the DFSS process is followed, the questions that must be asked and answered are quantitative but also conceptual in nature and involve far more than reliability methods. Typically, there is a multidimensional, multidisciplinary systems engineering aspect to the problem under consideration, and this leads to a multidimensional process for the application of DFSS principles.

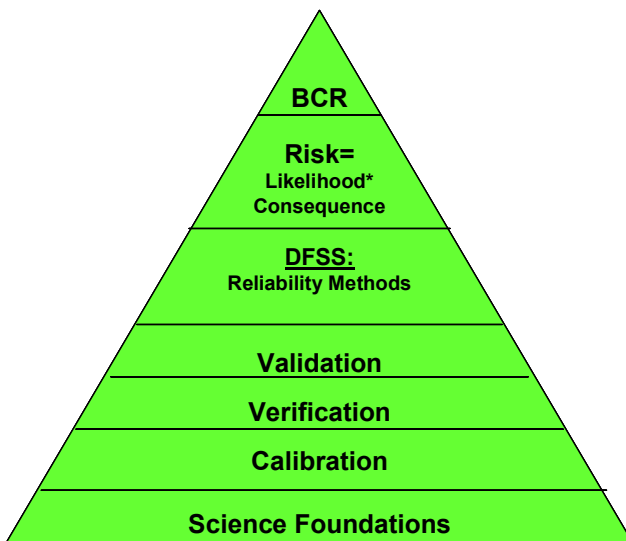


Figure 2. Pyramid of activity for the research and development needed as part of a DFSS solution for systems engineering.

We will show one fairly simple, self-contained example of the use of BCR below, with quantitative values, to convert a multi-disciplinary, multi-dimensional Pareto frontier (Wilson et al, 2000) into one suitable for the generation of a scalar BCR. In reality, a scalar BCR will itself have a range depending on the probabilistic or evidence based ranges for the dollar values involved, and for the benefit \$B weightings given for the various multi-dimensional elements. In the product design process, a common first-order simplification is the reduction of the multi-dimensional components of mechanical stress and strain (tensors) into scalar measures called “effective stress” and “effective strain”. Combining multi-dimensional customer wants and Critical-To-Quality (CTQ)

elements of a product into a single scalar metric like the BCR is not unlike combining the stress and strain tensors into scalars; the gain in simplicity must be balanced against the loss of detailed information.

Today, we might routinely deploy a DFSS process for any such undertaking with consequences that involve personnel safety, with elements such as QFD and BCR explicitly included. Over a decade ago, these methods were not the norm in general. However, many of the elements of DFSS, in a DCOV implementation sense, were carried out in the initial explosives handling decisions. Even implicitly, the BCR was considered, but only in a *qualitative* sense. The benefits of successful, safe operations with explosives were defined goals such as personnel safety, ability to respond to the weapon system requirements of the DOE and DoD, and providing data to advance our ability to model accurately with computer codes and models. Any quantitative analysis of a safety issue is of course complex, and depends on scenarios and assumptions regarding product value, accident consequences, and other factors. We have examined numerous complex methods for generating an explosives impact safety BCR, as discussed in (Logan et al, 2005). but for the purpose of following the DFSS process, it is really only necessary to convince ourselves that our product has, by some measure, a sufficiently positive BCR. A high BCR gives us “room” for a decrease in \$B or an unanticipated increase in \$C that might evolve during product design, development, or deployment.

The point of this short, very simplified narrative about the BCR is that it is desirable to have quantitative assessments of the BCR during the DFSS process; the BCR can quantify the best future course and help justify the funds needed. However, even without a quantitative value for the BCR, we can make several points regarding the application of DFSS to a large undertaking such as accident safety during explosives handling. The points are that:

1. There are simple and complex quantifications of a high BCR for assessments and mitigation measures for explosives handling safety.
2. On a personnel safety and public perception basis alone, we have a situation that compels the principles of both DFSS and Six-Sigma; and plenty of room for continued R&D investments to continue to reduce our assessed P_{fail} .
3. As we continue explosives safety testing and handling and enter the “V” phase of DCOV or DMADV, the features of the DFSS and then Six-Sigma process and roadmaps can provide quantitative guidance to future process control and R&D.

3 The Multi-Dimensional Pareto Frontier

In assuring safety during high explosive handling and logistics processes, several CTQ issues are faced at the same time. For example:

1. We need to determine the types of impact scenarios that exist, and determine the ones can be cost-effectively ruled out by using physical or administrative controls to prevent an impact scenario from being possible.
2. We need to determine the acceptable level of risk likelihood for a high explosive (HE) reaction, given any of the set of credible impacts that remain after the implementation of these physical and administrative controls.
3. We need to assess, using a combination of the best experimental and modeling tools available, the likelihood of HE reaction for each impact scenario, and whether the assessed likelihood is lower than the allowable.

4. We need to establish a path forward to improve our ability to assess the HE impacts and reaction likelihoods, with a case built on the relative benefits of experiments, model development, or both.
5. We need to use the Benefit/Cost Ratio to trade off the cost of these multi-dimensional aspects against cost.

The CTQ elements named above all remain to be traded off against each other and against cost. We will show one way to quantify the challenges faced above as part of a DMADV style implementation of DFSS. We will then attempt to quantify each of the four challenges, and generate suitable metrics for DFSS that are compatible in the same quantitative design trade space, and compatible with our own Design Safety Standards (DSS) already in use (Murray et al, 2004). The main output of this trade space will be to quantify the options for the path forward regarding investments in experiments and models to assess the likelihood of HE reaction. Since R&D can go on “forever”, it is important to have measures of benefit and cost to assure sponsors (in this case the Congress and the taxpayers) that we have criteria for knowing when more R&D is worthwhile, and when to stop.

We will capture the quantitative aspects of our R&D benefit / cost analysis as a single metric (the BCR or its predecessors) compiled from the multi-dimensional trade space. A simple example, based on a recently completed automotive design study, will help to illustrate the elements and how they lead to a single scalar metric indicator of the best path forward.

4 Example: Quantifying Multi-Dimensional Trade Space

First, we will clarify what is meant by metrics for DFSS that are compatible in the same quantitative design trade space. We can do this by revisiting a recent example of “exhaust system manifold development through multi-attribute system design optimization”, which is the title of the recent work by (Usan et al, 2005). We will revisit this work and give an example of one way to construct a set of metrics that can condense a Pareto frontier of Multi-disciplinary Design Optimization (MDO) into a single decision quantity, the Benefit / Cost Ratio (BCR). The BCR will be useful when we return to the DFSS and DCOV analysis for the HE impact safety as well.

(Usan et al, 2005) discuss MDO in terms of an automotive maniverter (see Figure 3; exhaust manifold with catalytic converter). An automotive exhaust system carries exhaust gases from the engine’s combustion chamber to the atmosphere. Exhaust gases typically leave the engine in a cast or tubular manifold, then through a catalytic converter, and then through a silencing sub-system before exiting through the tailpipe. Chemical reactions inside the catalytic converter change most of the hydrocarbons and carbon monoxide produced by the engine into water vapor and carbon dioxide, while the muffler attenuates the noise produced by the engine. Exhaust passages from each port in the engine enter the exhaust manifold, and then join into a common single passage before they reach the manifold flange. An exhaust pipe is connected to the exhaust manifold flange. Sometimes, a catalytic converter is moved upstream from the traditional underfloor position and is placed just after the point where pipes coming out of the engine ports join. This particular position is selected in order to achieve a reduction in the converter warm up time after the engine is cranked-up and consequently to speed-up the start of pollutant conversion. In this case, quite often the term “maniverter” (manifold+converter) is used.

(Usan et al, 2005) present an excellent discussion on the need for more efficient product development activities. They choose design options and tradeoffs for a specific maniverter as an example requiring MDO integration. Four metrics are chosen (same as the number of HE impact safety design engineering challenges we choose), plus maniverter cost. These metrics comprise:

1. F_1 , the first natural frequency of the maniverter (important for noise, vibration and harshness (NVH), and also related failure potential. Units are inverse time.
2. T_{IN} , Weighted average catalytic converter inlet temperature (important for converter efficiency). Units are degrees C.
3. M_m , maniverter mass (important for vehicle performance: acceleration, fuel mileage, handling). Units are grams.
4. TPI, the Torque Performance Index (important for acceleration and driveability). TPI is unitless, defined as $TPI = (\mu_T / \sigma_T)^2$, where μ_T = Mean Torque output over the driving range, and σ_T = the standard deviation of torque output over that range. This TPI is simply the signal-to-noise or SN ratio as defined by (Taguchi, 1987).
5. \$C, maniverter Cost (trades off against the above). Units are Euros, or dollars in this work.

Prior to normalization, each of these metrics has different units, but a scalar value. In (Usan et al, 2005), a rapid, highly automated design tool set is used to converge on an example set of twelve final design choices for the maniverter. The values for F_1 , T_{IN} , M_m , TPI, and \$C for each of these twelve designs (a thru l) are presented as a color "Rainbow Plot" in (Usan et al, 2005). A similar plot is shown in gray scale in Figure 4, where darker gray is a better choice and lighter gray is a worse choice. Usan et al. choose design 'b' as the 1st choice, and also note some 2nd and 3rd choice suggestions. These choices are somewhat intuitive from the rainbow plot, but remain subjective due to the incompatible units of the five metrics.

We can show the multi-dimensional Pareto frontier with the actual numbers, as shown in Table 1, again after (Usan et al, 2005). It is perhaps even less clear how to choose the preferred design from this maze of numbers, all with different units. In Table 1, the "Base" design is shown as well as the twelve excursions. Careful study of the numbers will likely result in an intuitive feel that Design 'b' is in fact quite preferable to the base design. Some type of normalization must be performed to compare across the 5 metrics. Weighting factors are used in (Usan et al, 2005) resulting in a dimensionless metric with a scale as shown in Figure 4.

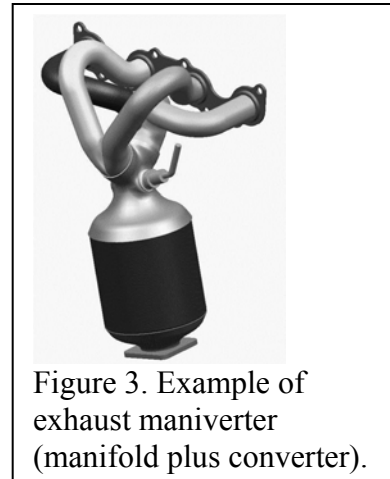


Figure 3. Example of exhaust maniverter (manifold plus converter).

	Design	Freq F1	Temp T-IN	Mass Mm, gm	TPI	Cost \$C	Metric Value Shading from Usan et al
	a	~		○	○		0.8-1.0
1	b		x	x			○ 0.6-0.8
	c	x		○	○		x 0.4-0.6
2	d						~ 0.2-0.4
	e		x			○	0.0-0.2
3	f					○	
	g		x			○	
	h		x			○	
	i	~				○	
	j		x	~		○	
	k	○	x	~		x	
	l		x	~			

Figure 4. Pareto Data “Qualitative Rainbow Plot”. Color rainbow of (Usan et al, 2005) converted to the gray scale as shown by the shading key to the right of the table.

As an alternative to this dimensionless normalization, we will attempt to capture the multi-dimensional nature of the maniverter design tradeoffs with a single Benefit / Cost Ratio (BCR). We will present only a scalar BCR for each design excursion in this example. We used the following assumptions and sources to convert each metric to a dollar \$B basis:

F1: We assume that vibration failure due to F1 would go as $(1/F1)^2$. This means practically, as the numbers in Table 1 show, that most of the designs would incur a negligible penalty in benefit \$B except for the low-F1 designs ‘a’ and ‘f’. If we choose a constant such that about a \$2000 repair and customer cost is incurred for design ‘a’ and ‘f’, the other designs suffer a negative \$B that is small in comparison.

T_{IN}: We assumed an average grams-per-mile emissions and social costs from various sources including (Teller et al, 1997), (Matthews, 2000), (DOE, 1997), (EPA, 1999), and (Kiely, 1997). We further postulate for this example study a decrease in emissions with higher T_{IN}, with an average of a 1% decrease in emissions per 20°C increase in T_{IN} above 800°C, per (Shamim et al, 1999) and assume this as a linear relationship. This gives a \$B for lower social cost of emissions, assumed over a 120,000 mile vehicle life.

M_m, grams. We assumed a weight penalty of about \$4/lb. or \$0.009/gm.

TPI: We postulate a constant $\sigma_T = 10$ ft-lb torque, and then calculate the gain in mean torque μ_T from the reported values of TPI. We assign a value of \$B = \$20 per ft-lb of mean torque. This is a fairly conservative (low) value compared to the retail market demand, but we will still see that TPI emerges as the dominant factor in the BCR analysis.

\$C: We converted the cost reported in (Usan et al, 2005) from Euros to dollars at \$1.30 per Euro.

Table 1.
Pareto data “Quantitative Rainbow Plot”.

Design	Freq F1	Temp T-IN	Mass Mn, gm	TPI	Cost \$C
BASE	340.71	1178.68	5945.63	129.70	36.83
a	4.93	1188.88	5238.26	136.01	15.83
b	415.26	1204.38	5556.17	152.96	18.56
c	319.92	1190.33	5150.39	133.48	25.28
d	268.17	1183.06	4806.43	70.79	28.49
e	440.08	1208.98	6266.49	139.27	35.09
f	3.48	1183.89	4818.21	70.62	35.27
g	91.00	1210.14	6146.74	139.31	35.47
h	442.18	1209.00	6208.10	139.20	39.16
i	346.86	1234.46	6019.93	137.27	40.64
j	236.31	1208.38	5647.09	138.67	42.43
k	361.97	1210.38	5689.49	138.36	61.50
l	243.15	1210.02	5853.49	139.45	92.64

We can now compute the \$B for each of the 5 metrics and 12 designs in Table 1. These are shown in Table 2, along with the BCR, the sum of the four \$B divided by \$C for each design. Also shown in Table 2 are the top few choices for the maniverter design, based on $BCR = \$B / \C , or on Net $\$B - \C , as well as the choices from (Usan et al, 2005). Judgment in looking at the individual values plays an important role in design choice. The estimates we used in converting the metrics F1, T_{IN} , M_m , and TPI to a dollar benefit, while reasonable, are certainly not of the pedigree desired for a design decision; we simply provide these for an

example. In reality, assigning dollar values to the costs and benefits in BCR should receive the same diligence and probabilistic considerations (Leopoulos et al, 2003) as the rest of the DFSS aspects. The BCR offers a way to quantitatively capture this information as a scalar. Close examination of Table 2 shows how the BCR or Net \$B can provide a quantitative scalar assessment of the design options, with the top few choices marked as ‘1’, ‘2’, or ‘3’ etc. These compare well (but not identically) to the choices suggested in (Usan et al, 2005) from their Pareto Rainbow charts. Either BCR or Net \$B or both could be viewed as a scalar roll up of CTQ metrics.

Figure 5 conveys a histogram of the total BCR; *the choices for maximum BCR are now obvious*. The histogram style presentation as in Figure 3 makes quantified expression of the “best design choices” obvious; if for some reason Design ‘b’ were rejected, the next best choices based on BCR are obvious too. If detail is desired, the \$B and \$C values in Table 2 can be compared or examined in graphical form to provide more detail as to which components of the design are dominating the final outcome.

Table 2. Pareto data converted to \$B and \$C, with total BCR for each design.

						Freq F1	Temp T-IN	Mass Mn, gm	TPI	Cost Dollars \$C
Best (Usan)	Best (BCR)	Best \$B-\$C	Design	BCR	\$B total	\$B	\$B	\$B	\$B	\$C
			BASE	11.79	564.59	-0.43	340.812	-53.511	277.718	47.879
			a	-69.09	-1421.90	-2057.20	349.974	-47.144	332.467	20.579
1	1	1	b	32.63	787.19	-0.29	363.942	-50.006	473.54	24.128
	2		c	18.72	615.13	-0.49	351.297	-46.354	310.671	32.864
			d	-0.44	-16.46	-0.70	344.754	-43.258	-317.26	37.037
2	3	3	e	14.72	671.66	-0.26	368.064	-56.398	360.254	45.617
			f	-90.44	-4146.73	-4128.68	345.501	-44.264	-319.29	45.851
3	4	4	g	14.49	668.36	-6.04	369.126	-55.321	360.593	46.111
3	5	6	h	13.19	671.63	-0.26	368.1	-55.873	359.661	50.908
3	6	2	i	12.86	679.66	-0.42	391.014	-54.179	343.246	52.832
		5	j	12.27	676.76	-0.90	367.542	-53.524	363.641	55.159
			k	8.38	670.29	-0.38	369.342	-51.205	352.531	79.95
			l	5.62	677.27	-0.85	369.018	-52.681	361.779	120.432

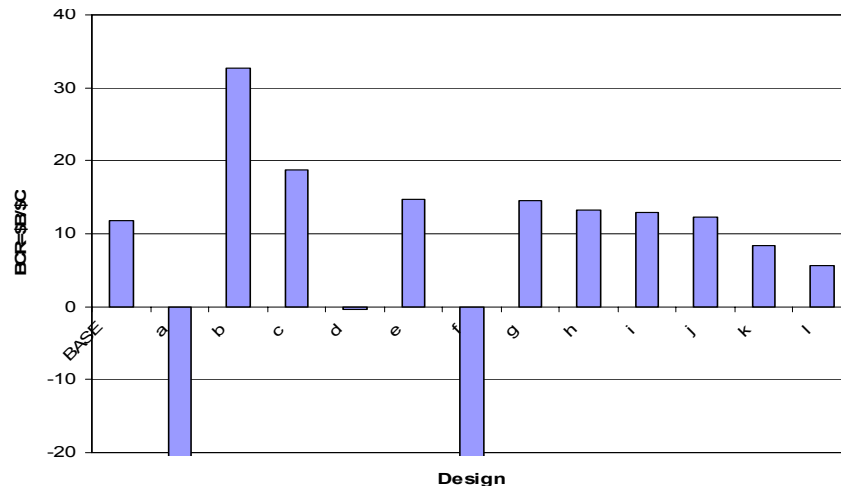


Figure 5. Total BCR of the BASE design and the twelve design options (a through l). Raw data from (Usan et al, 2005); BCR analysis from this work.

5 Revisit of Explosive Impact Safety with DFSS / DMADV

Given the discussion above of our views on DFSS, use of the BCR, and the Maniventer example of converting a multi-dimensional design frontier into a scalar, let revisit, from a DFSS perspective, the high explosive impact safety issue as discussed in (Nitta et al, 2004) and look at the five CTQ issues we raised for this issue at the start of Section 3:

1. Using the best combination of administrative and physical controls available to prevent scenarios where an HE impact is even possible leaves us with the necessity to assess likelihood of impact for a set of impact conditions similar to the impactors shown in Figure 6.
2. The overall assessed likelihood of the combination of an HE impact occurring and leading to a reaction must be less than 10^{-n} where $n \gg 6$; this overall allowable puts us clearly into DFSS process thinking. Use of administrative and physical controls leaves us with the requirement to assess that the likelihood of reaction, given that an impact occurs, might be, for example, less than 10^{-2} .
3. Given this example "requirement", we need to assess, with models and experiments, the types of impacts shown in Figure 6, and see if the probability of "failure" (i.e., any HE reaction) is indeed less than 10^{-2} , or in other words that the Reliability of seeing no HE reaction in this hypothetical case is $R > (1 - P_{\text{fail}})$ or $R > 0.99$.
4. We will discuss the nature of the measures used to assess the HE impact and potential for reactions against this hypothetical example requirement of $R > 0.99$, and how the data and models available as shown in (Nitta et al, 2004) might be augmented to allow us to improve the robustness of our assessment that we meet the $R > 0.99$ criteria we chose for the example of this work.
5. Use of the Benefit / Cost Ratio (BCR) to balance the benefits of more research investment for risk reduction against the cost of those research investments. A high BCR can defend our research funds from unwarranted raids at budget time; a low BCR says we should move on to a new research area or a new scenario.

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In the analysis of (Nitta et al, 2004), we used a more conservative (harsh) measure of model-assessed “likelihood” of HE reaction. For example, for the Steven 30mm impactor shown in Figure 6, with the explosive type PBX 9404, our simple analytical regression model assessed a reaction likelihood of

$$L_{\text{fail}} = 0.252$$

Since our requirement for this example is $P_{\text{fail}} < 0.01$, it appears that we are using a fairly

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harsh metric for assessment of failure, or that our model needs improvement, or that we need more experimental data (or some combination of the above). If the same model and data that generated the $L_{\text{fail}}=0.252$ (the scenario in Table III of Nitta et al, 2004) were used to assess P_{fail} , we would assess a nominal reliability for avoiding an HE reaction of:

$$\beta = \text{Reliability Index} = \text{RI} = 2.88, \text{Reliability } R_{\text{NoRxn}} = 0.9980$$

$$P_{\text{fail}} = 1 - R_{\text{NoRxn}} = 0.0020$$

This P_{fail} , expressed as the complement of mean assessed reliability, clearly meets our $P_{\text{fail}} < 0.01$ requirement.

We can also examine this example “model assessed reliability” at a fairly high confidence level of 3 standard deviations or 3σ , and if we assess reliability using the estimate of experimental uncertainty only ($1\sigma \sim 2$ m/s in impact velocity needed for an HE reaction) we obtain:

$$\beta = \text{Reliability Index} = \text{RI} = 3.31, \text{Reliability } R_{\text{NoRxn}} = 0.9995$$

$$P_{\text{fail}} = 1 - R_{\text{NoRxn}} = 0.0005$$

This P_{fail} , expressed as the complement of mean assessed reliability, again clearly meets our $P_{\text{fail}} < 0.01$ requirement.

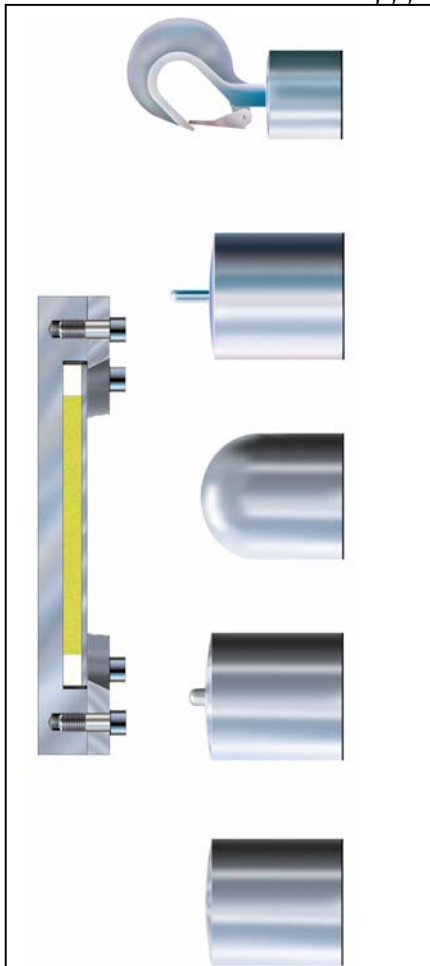


Figure 6. Impact assembly (Switzer et al, 2003) containing flat cylinder of high explosive and surrounding components, and range of representative impactors. Our example uses the original “Steven” impactor, with the fully rounded (30mm radius) head.

If we look back at the three main DFSS points raised in the introduction, we can note that:

1. We have shown that the DFSS can quantify aspects of our judgment. We chose an example $P_{\text{fail}} < 0.01$ criteria and showed that with a Reliability method based either on mean reliability, or on reliability that considers available experimental variability

- information only, we can meet this example requirement.
2. If we use the full model based assessment as in (Nitta et al, 2004), we can only assess $L_{fail}=0.252$. This says that our model is not yet adequate to assess a full range of impact scenarios that may be far from our experimental data, even though we meet the CTQ measure of $P_{fail}<0.010$ using the experimental data locally or using a mean reliability measure. This leads to our third point.
 3. We showed that DFSS is a process that needs periodic revisit. In addition to the DMADV steps of Define, Measure, Analyze, Design, Verify, a step called “O” or “Optimize” is often added to form a DMADOV implementation of DFSS. For example, if our HE impact scenarios begin to stray very far from the experimental data, we can no longer rely on the mean reliability or variability based $P_{fail}\sim 0.001$, and must seek model and experimental augmentations to enable us to reach a model-assessed $L_{fail} < 0.01$ for any new HE impact scenarios far from the database. In (Nitta et al, 2004), we generated estimates of the BCR for improving our impact models and obtaining more data. A range from BCR=7 to BCR=42 was achieved. Viewed as a revisit of DFSS, this is a way to quantify the value – and hence recommend a path forward – for more research on explosive reactions during impact.

6 Conclusions

We showed how to work with single metrics for DFSS (BCR or equivalent) to clarify a quantitative path forward. With conversion of multi-disciplinary and multi-dimensional Pareto frontier metrics into a single BCR metric, clear choices emerged for the maniverter example. Regarding the safety example and the data and model for high explosive (HE) reaction on impact, quantitative justification for the path forward emerged – this time, with a linkage to the reliability R and $P_{fail} = 1 - R$ elements so closely linked to our own LLNL Design Safety Standards and risk-based design requirements. More R&D for HE impact safety is an obvious thing to do, but we now have a way, using DFSS and associated metrics like the BCR, to quantify the value of this R&D, what we can gain, and when we will reach the “good enough” point and transition from Design For Six Sigma and DMADOV into Six-Sigma and DMAIC.

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